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Accuracy of Geomagnetic Absolute Observation caused by Azimuth Mark Reading

by

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Summary

For the observation of magnetic declination and inclination at Kakioka, a DI-72 Type theodolite instrument is used. Consolidating and summarizing those measurements resulted in poorer observation accuracy for declination than for inclination. We ascribed this to poor azimuth mark observation accuracy and reviewed the measurements anew from this point of view. As a result, it was confirmed as expected that the poor accuracy of the declination measurement is attributable to the poor accuracy of azimuth mark observation.

Based on this result, we proposed increasing the number of azimuth mark measurements to improve the azimuth mark observation accuracy in routine geomagnetic absolute observation. At the same time, the effects of increasing the observation time and using different azimuth marks were examined. As a result, it was found that accuracy improvement can be expected from these measures in azimuth mark observation and, consequently, in declination observation without imposing a heavy burden.

1. Introduction

Calibration observation (geomagnetic absolute observation) takes place at a frequency of about once a week. This observation is used for "calibration of the base of continuous measurement value" due to continuous geomagnetic variation observation instruments (fluxgate magnetometer, proton magnetometer, Overhauser magnetometer, and others, collectively called the variation observation equipment hereinafter) and observation points. That is, the baseline value of the variation observation equipment is determined at this occasion (so it is called the adopted observation baseline value). Where no observed baseline value is available, the baseline value is found by interpolation between available observed baseline values in consideration of the fluctuations of installation conditions of the variation observation equipment (detector temperature and detection level fluctuations and occurrence of artificial disturbances).

The magnetic field intensity and direction at an arbitrary time can be found by adding the baseline value to the observed variation value. This means that the accuracy of geomagnetic absolute observation affects the exactness or reliability of the published values.

The basic elements of geomagnetic absolute measurement at the Kakioka Magnetic Observatory are declination (D) and inclination (I) by DI-72 Type theodolite and the total magnetic force (F) by the MO-PK proton magnetometer. Considering that the other force components (horizontal component H and vertical component Z) can be found by calculation and combination of the basic elements, it is desirable that the basic elements have about the same observation accuracy.

The measured values seem to lack directional accuracy (declination accuracy in particular) compared to magnetic field intensity (F). This article reports investigation results about the accuracy of absolute declination measurement and proposes a technique to improve the measurement accuracy.

2. Variance of declination and inclination baseline value

For the fluxgate magnetometer 90FM at Kakioka, the baseline values of declination (the angle calculated from the magnetic field intensity measured by a 90FM detector (H) directed to the magnetic north and another detector placed in a perpendicular direction in a horizontal plane) and inclination (the angle calculated from F by the Overhauser magnetometer and H by the 90FM) are plotted in Fig. 1. In this figure, abscissa denotes the number of days starting on April 1, 2001 and ordinate denotes the magnitude of baseline value fluctuations.

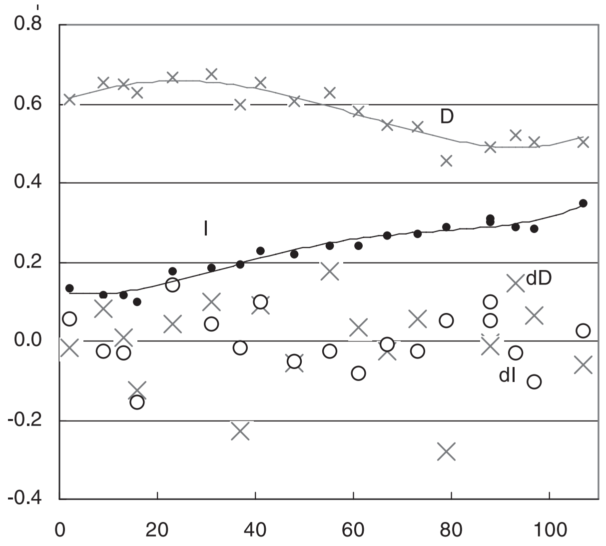

Fig. 1 Variation and fluctuation of observed baseline value

Both baseline values fluctuate slowly with a constant amplitude. That is, a slow fluctuation occurs with a period of about 3 months and an amplitude of 0.1 to 0.2 minutes (equal to 10 seconds of arc) and this is a "fluctuation due to the fluctuating measured values" that can be accounted for by the level fluctuations of the 90FM detector (level fluctuation of the detector mount) and the temperature fluctuations of the detector.

"The fluctuation with a short period" seems to have an amplitude of 5 seconds (D) and 3 seconds (I) and cannot be accounted for by the temperature and level fluctuations of the 90FM detector. There is a similar movement in the baseline values of the Overhauser magnetometer obtained using the same absolute observation values. From these situations, the variance of observation values seen in Fig. 1 can be judged to be attributable to the absolute observation values. By allowing the plot of D and I baseline values to be represented by one smooth curve and plotting the residue after subtracting the curve's ordinate from each value, one obtains dD (X-marks) and dI (circle marks) in the figure (to make the graph prominent, actual dD and dI are magnified 5 times).

The standard deviation of declination D and inclination I is found to be D: 0.023′ and I: 0.015′, that is, declination D is larger, albeit slightly, than inclination I. Incidentally, as a cause for accuracy degradation due to absolute observation values, several factors are plausible. For example, errors occur when searching for the magnetic field direction (with a theodolite, zero output of the search coil is detected on a synchroscope), reading the scale plate of the magnetic theodolite, and correcting the tilt of the magnetic theodolite level. These errors are contained in the declination and inclination in about the same amount.

For the measurement of declination, it is indispensable to project the geometrical north onto the magnetic theodolite scale. This can be found by observing the azimuth mark (the deviation from the true north is determined beforehand by Polaris observation). If the observation accuracy of the geometrical north is poor, the accuracy of the observed declination values (baseline value of the declination component of continuous observation values) becomes poor.

For absolute observation at Kakioka, the installation conditions of the magnetic theodolite are not usually altered for several months. Because the positional relations between the azimuth mark and magnetic theodolite do not change as a matter of course, the reading of the azimuth mark on the magnetic theodolite scale should not change. However, actual measurements do change. Taking this survey as an example, a difference of 0.1 minutes of arc (6 seconds) occurs for about 3 months. For this data, the relationship between declination baseline value and azimuth mark reading is as shown in Fig. 2. There seems to be a correlation between the two (correlation coefficient 0.6).

From the data in Figs. 1 and 2, the variations

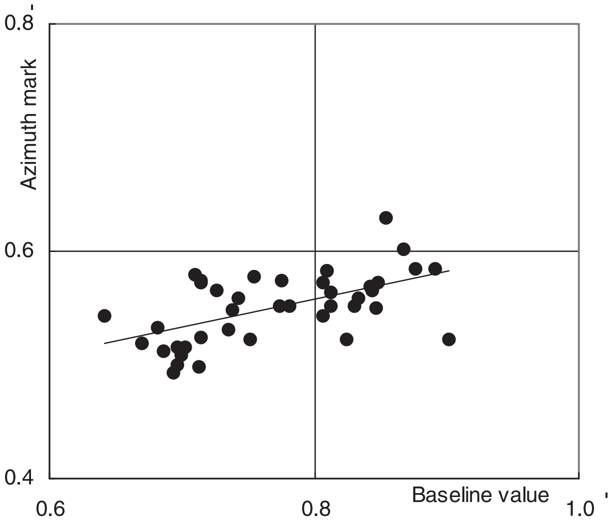

Fig. 2 Correlation between declination baseline value and azimuth mark reading

of declination baseline values are larger than the inclination baseline value and it is inferred that the true north determination accuracy (azimuth mark reading accuracy) is related to this in some way. Compared to the baseline values of horizontal force component (H) and vertical force component (Z) found from the observed inclination baseline values in combination with the total magnetic force value (F) of about one digit higher accuracy (all the continuous observation instruments are fluxgate magnetometers), the variance of declination baseline values is large, and this is true not only at Kakioka, but also at other observation points (Memanbetsu, Kanoya, Chichijima, and Haraigawa) and obvious from the annually held "Technical Study Meeting Standing Subject Data." It is inferred that not only with the observation results by the DI-72 Type theodolite, but also with the observation by the FT Type magnetic theodolite, the declination observation accuracy becomes poor because of the influence of azimuth mark observation accuracy.

Under the "Rules for Commissioned Inspection of Meteorological Instrumentation" and "Rules for Internal Inspection of Meteorological Instruments at Meteorological Agencies," the Kakioka Magnetic Observatory is designated as a governmental agency to inspect magnetic theodolites, magnetometers and other instruments. The observation for the inspection and pass-fail decision is performed by the Observation Section in charge. Instruments of the accuracy discussed in this article are treated as Magnetic Theodolite class 1, whose borderline between pass and fail is at an instrumental error of 0.2 minutes of arc, so the observation accuracy in this article will never cause problems. For the internal inspection, however, the instrumental error of a magnetometer used at the Headquarters in particular and at branches is determined against the Kakioka Standard Instrument (DI-72 Type theodolite at present) in units of 0.01 minutes of arc. One of the duties of a standard observatory is to satisfy this accuracy.

Of recent magnetic theodolites, FT type magnetic theodolite (a declination and inclination measuring instrument, also called a DI meter) is prevalent and its observation results for the inspection are shown in Fig. 3. The series of observed values connected by line segments indicate the instrumental error from the results of an observation with the same instrument and during the same period (2 or 3 days in general). One series of observations includes at least 5 and at most 10 observations, and one observation is performed by the same observer and takes about one hour.

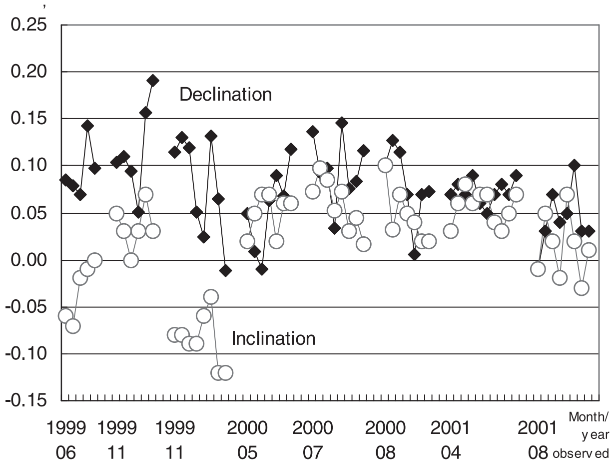

Fig. 3 Fluctuation of measured values by FT Type magnetic theodolite

What should be noted in this figure is the variation among the observed values connected by line segments. These observed values should basically take the same value. However, the figure indicates a variation of about 0.1 minutes of arc to as large as about 0.15 minutes of arc. This variation cannot be regarded as ascribable to the continuous geomagnetic observation instruments

(90FM and OHM) used for the correction of geomagnetic fluctuation with time. This is because the period of one series of observations ends in two or three days, so level fluctuations of the continuous observation instrument or other baseline value fluctuating factors are hardly feasible unless there is a heavy rain. The error in observed absolute values is presumably the largest factor. Compared to inclination (open circles in the figure), the variation of declination components (black diamonds) is large, and this is inferred to be attributable to the poor azimuth mark reading accuracy as with the observation by the above-stated theodolite. Incidentally, the standard deviation of each block is as follows:

Mean standard deviation of observed declination values: 0.036′ ,
Maximum standard deviation of the same: 0.05′
Mean standard deviation of observed inclination values: 0.026′ ,
Maximum standard deviation of the same: 0.03′

3. Accuracy of azimuth mark read values and observed declination values

At Kakioka, absolute observation using DI-72 Type theodolite is performed at a frequency of once a week or so. The time taken for one absolute observation is about 3 hours including the calculation and consolidation of absolute observation data and the baseline value calculation from fluctuating measured values. Excluding the preparation before and data consolidation after the observation, the net observation time (time while operating the theodolite) is about a half, or 90 minutes or so. Of this time, about 20 minutes are consumed with azimuth mark observation.

Absolute declination observation consists of observation to find geographic north by peering through the telescope (called the azimuth mark observation) and observation to search for magnetic north by turning the search coil (tentatively called the magnetic field azimuth observation though it is an uncommon term). In one day, the magnetic field direction observation takes place 32 times and the azimuth mark observation takes place 16 times to establish 8 baseline values. The 8 baseline values are divided into the first and second halves and shared by two observers (that is, one observer establishes 4 baseline values). If there is no observational error, the four baseline values should be the same. Similarly, the 16 read values obtained by peering through the telescope should be the same (because the telescope does not lie at the center of the magnetic theodolite, a difference of about 5 seconds occurs when it is turned horizontally; however, it is assumed that this has been corrected). However, they do not take the same value but vary. The variation of these two observation quantities is shown in terms of standard deviation in Fig. 4.

One sees that, compared to the observed magnetic field azimuth values, the observed azimuth mark values have a large variation (standard deviation). The mean standard deviation is 0.01′ for the observed magnetic field azimuth values and 0.03′ for the observed azimuth mark values. For both magnetic field azimuth observation and azimuth mark observation, the current technique is to let the mean of the observed

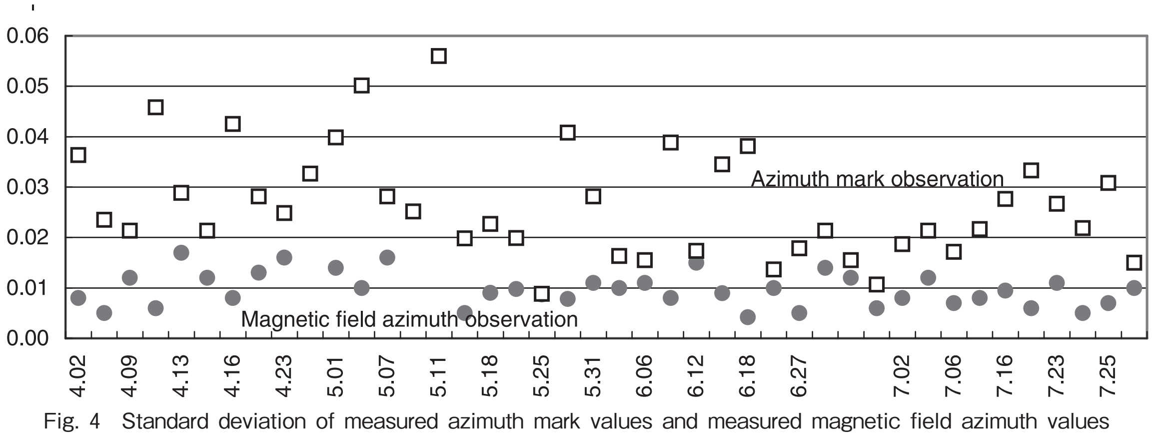

Fig. 4 Standard deviation of measured azimuth mark values and measured magnetic field azimuth values

values of that day represent the observation (the baseline value based on the observed values is called the employed observed baseline value). The accuracy (95% confidence interval) is estimated from the number of observations, variation of the observed values and a t-distribution table, as follows:

For observed magnetic field azimuth values: 0.01′
and for observed azimuth mark values: 0.02′

Because the observed absolute declination value can be found as the simple difference between magnetic azimuth and geographic azimuth, the accuracy of azimuth mark observation, which is poorer in accuracy, governs the accuracy of the observed absolute declination values. To improve the declination observation accuracy, the first priority is to improve the accuracy of the observed azimuth mark values.

Several methods are plausible to improve the azimuth mark measurement. For example, one method is to improve the resolving power of the telescope mounted on the magnetic theodolite by increasing its magnification factor. Another one is to make the azimuth mark more easily visible by improving its target, as attempted at Memanbetsu. It is also good to eliminate the aiming error due to shimmer or other disturbances within the visibility range by some means. At any rate, problems will arise in expenditures on remodeling of the magnetic theodolite, azimuth mark and other instruments.

The easiest and simplest executable method is to increase the number of times of azimuth mark observation (the number of times of peering at the azimuth mark through the telescope) and thereby narrow the confidence interval of the mean. If azimuth mark observation is performed 32 times, or twice the current 16 times, the confidence interval of the mean will become ±0.01′. It goes without saying that increasing the number of observations results in an increase in the required observation time. As the time increment, the current 20 minutes will be simply added, and the net observation time will increase from 90 minutes to 110 minutes. In terms of the required time including data compiling, it only increases from 3 hours (180 minutes) to 200 minutes (11% increase).

However, considering the work pattern, that is, work starts at 8:30 and the boundary of a day of the Coordinated Universal Time is at 9:00, an increase of 20 minutes cannot be neglected. There is a possibility that part of the data consolidation is carried over into the work hours in the afternoon and hinders the start of infrequent "afternoon re-observation." Nevertheless, increasing the number of azimuth mark observations leads to an accuracy improvement of absolute declination observation and, consequently, declination observations including those performed at an arbitrary time. Thus, we propose this measure.

On the occasion of an instrumental error observation of FT Type magnetic theodolite, an experiment was attempted to improve the declination observation accuracy by doubling the number of azimuth mark observations. In the experiment, the usual number of times of reading the azimuth mark was not simply doubled, but a dummy azimuth mark is made at the position about 180 meters north of the observation point (a cross mark drawn on a wall of the second fluctuation observation instrument room) and the read values of this azimuth mark were superimposed on the usual azimuth mark read values. Results of this instrumental error observation are shown in Fig. 5. D1 (●) in the figure indicates the instrumental error when only the usual azimuth mark is used and D2(□) indicates the instrumental error obtained additionally using the read values of the dummy azimuth mark. The variation of the

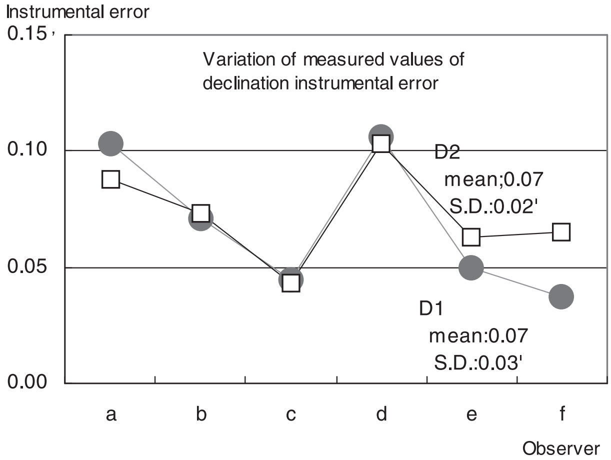

Fig. 5 Variation of measured values of declination instrumental error

declination instrumental error obtained independently by 6 observers is smaller for D2 than for D1. No difference was observed between the instrumental error calculated using the read values of the usual azimuth mark only (and averaged over the 6 observers) and the instrumental error calculated using the read values of the dummy azimuth mark in addition (0.07ʹ in both cases). However, one will see that the variation decreased and the confidence interval of the mean became narrower by that amount (usual azimuth mark only: 0.07±0.03ʹ, dummy azimuth mark additionally used: 0.07±0.02ʹ).

By another method, the significance of increasing the number of observed azimuth mark values was investigated. Increasing the number of observed values results in improved accuracy, and conversely this means that decreasing the number of observed values will result in degraded accuracy. During the period of about 70 days from March 21 to May 31, 2001, absolute observation was performed 13 times and a baseline value was obtained each time. Of course, the mean of 16 azimuth mark observations was used in the usual manner. From this observation data, half, or eight observed azimuth mark values were extracted and taken as a sparse set of observed values, which was used to find the baseline anew.

During this period, there was no rapid change in the baseline value due to detector level or detector temperature fluctuations; however, there were temperature fluctuations of about 2℃, which were accompanied by a slow change in baseline value. The fluctuations of the baseline value due to the accuracy of absolute observation were found by removing the slow change from the baseline values found by the usual method (closed circles connected by line segments) and from the baseline values found anew from the half number of observed azimuth mark values (open circles), as shown in Fig. 6.

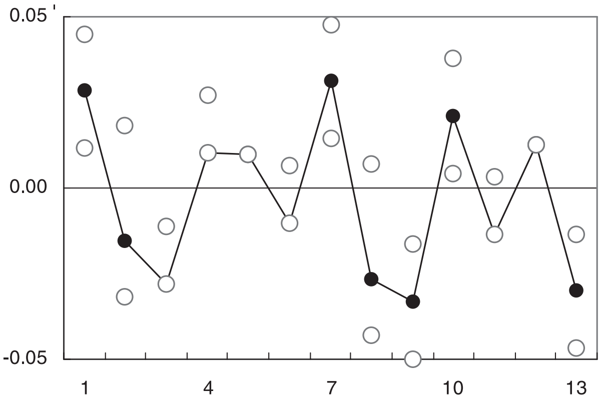

Fig. 6 Variation of baseline values depending on the number of azimuth mark observations

One will see a large fluctuation amplitude of the open circles compared to the closed circles. The fluctuation amplitude of the closed circles (±0.03ʹ) is the accuracy of the observed absolute declination values that will be obtained using the DI-72 Type theodolite and by the currently used method. This supports the inference that decreasing the number of observed azimuth mark values results in increased fluctuations of baseline value and degraded accuracy of absolute declination observation. As proposed in this article, the accuracy of observed declination values will be improved if the number of azimuth mark observations is increased.

4. Azimuth observation with different targets

The azimuth mark used in the comparative calibration room was installed in January 1997 and it has a total of 4 targets on the same concrete base. One is a target available on the market (the W3 Type target plate made by Asahi Seimitsu; called the commercial target hereinafter) and the other three are a stainless steel bar of 100-mm square in which three holes of different sizes are made (hole sizes are 5, 10 and 15 mm in diameter and called the small hole target, medium hole target and large hole target, respectively).

Based on various experiment results after installation, the large hole target has been employed for the current absolute observation after January 1998. An outline of the experiment results that determined the employment of the large hole target is as follows (cited from the Observation Section's archive material "On-premises Azimuth Targets - from installation to employment").

1. Visibility of the targets
   - ●The visibility of the small hole target is affected by weather conditions and the target cannot be seen when there is a severe shimmer.

- The visibility of the other 3 targets (commercial, medium hole and large hole) is different for different observers. If forced to rank them in terms of visibility, the large hole target comes first, followed by the commercial target, and the medium hole target is poorly visible.

2. Accuracy of aligning the telescope crosshairs with a target (variance of readings)
   - In observation with DI-72 Type theodolite, there is no difference among the 3 targets (commercial, medium hole and large hole). The variance of the large hole target is slightly smaller.
   - In observation with FT Type magnetic theodolite as well, there is no difference among the 3 targets (commercial, medium hole and large hole) and the variance of the large hole target is slightly smaller.

3. Difference of observed azimuth target value among observers (personal error)
   - For all targets, the personal error is smaller when FT Type magnetic theodolite is used than when DI-72 Type theodolite is used.
   - With DI-72 Type theodolite, the personal error is large when the large hole target is used. However, this is because the value of a particular observer is very different and, if this is removed, the personal error is small when the large hole target is used and large when the medium hole target is used. With FT Type magnetic theodolite, there is very little personal error.

Although not found at this point of time, there was concern about the commercial target that errors might be caused by the warp or other deformation of the target plate due to solar radiation or other form of heat, and it was dropped from the candidate targets in the employing process.

Now, let us consider using the commercial target in combination anew. If the number of azimuth mark readings is increased as proposed in the previous section, the same target will be seen so many times that a preconception may form in the observer (if the same observed value is not obtained, we are apt to interpret it as a misalignment or misreading). If so, there is concern that increasing the number of observations becomes meaningless.

The angle of view of the commercial and large hole targets was calculated from the data obtained at true azimuth observation after 1997, as shown in Fig. 7. ◆ indicates a value observed from the east platform of the comparative calibration room by DI-72 Type theodolite and ○ indicates a value observed from the west platform of the same room by FT Type magnetic theodolite. Calculating from the distance (193 meters) between the comparative calibration room and the azimuth mark and the distance (296 mm) between the two targets, the angle of view is 5.27 minutes of arc and this almost agrees with the mean of measurements.

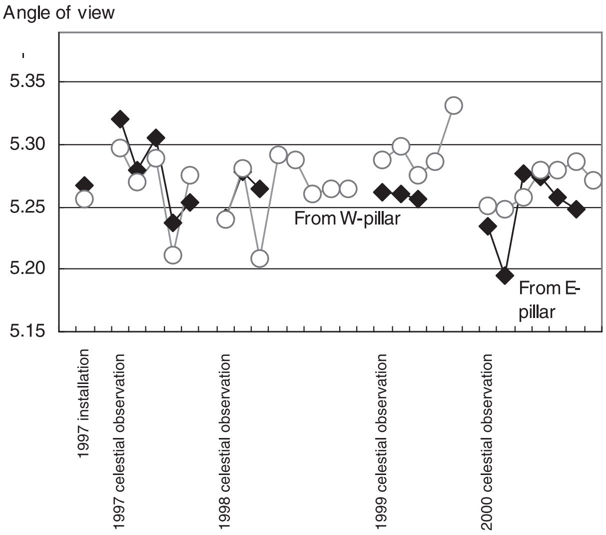

Fig. 7 Angle of view of commercial and large hole targets seen from comparative calibration room pillar

The fluctuations of the angle of view generally lie within 0.1' ±3". The expected accuracy of the azimuth mark reading is about 1.5 seconds of arc (described in §3), so it is inferred that the accuracy of the observed angle of view (difference between two observed azimuth mark values) is about 3 seconds of arch in the worst case. The data shown in Fig. 7 was made by several observers and contains personal error due to the tendencies of particular observers. For both the angle of view from the east platform and the angle of view from the west platform, no significant secular change is seen.

Based on these inferences, the angle of view has undergone no change for about 5 years. That is, it can be judged that, for the large hole target and commercial target installed on the same concrete base, their positional relationship (296 mm as of the measurement in August 2001) has not changed.

Another problem with the commercial target plate is a warp due to intense solar radiation in the daytime in the height of summer, and a question arises whether or not such a warp can bring the result that the target has apparently moved. Thus, a simple experimental observation was performed in this study and is presented in Fig. 8.

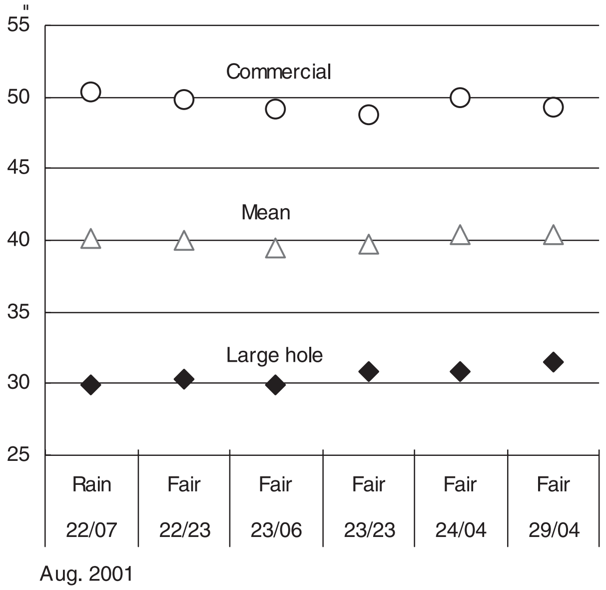

Fig. 8 Observed azimuth values using large hole and commercial targets

Ordinate denotes the observed azimuth values in seconds obtained using the commercial and large hole targets. Each observed value was obtained by one observer from the same number of times of peering through the telescope as the usual absolute observation (because the observer peers at the commercial target in addition to the large hole target, the number of times of peering is twice the usual observation). On the horizontal axis, the date and time (UTC) of observation and the weather at the observation are shown.

The experimental observation values of the commercial and large hole targets vary within an amplitude of 2 seconds of arc in general. The amplitude of this variation is equal to the confidence interval of the observed values (0.02' as mentioned above). Of the observed values of the commercial target, pay attention to the right two (observations at 04 on the 24th and 29th). They are not particularly peculiar compared to other measured values. That is, for the question of whether or not the readings of the commercial target are biased to a particular direction in the daytime of a fine day, the answer "there is no bias" was obtained as the original goal of this experimental observation.

There is no significant difference between targets in both the long-term fluctuations determined from the data in Fig. 7 and the fluctuations in one day in Fig. 8. This means that the anxiety about the commercial target, which caused concern when deciding the target to employ in 1998, is eliminated. It was proposed to increase the number of measured azimuth mark values at the usual absolute observation. Furthermore, we propose using the commercial target in addition to the currently used large hole target. Incidentally, the offset angle of the commercial target from true north is determined to be 0°46' 49"W (east platform) and 0°38' 14"E (west platform) from the employed offset angle of the currently used large hole target (east platform of the comparative calibration room: 0°52' 05"W and west platform of the same room: 0°32' 58"E) and the measured angle of view of the large hole and commercial targets (0°5' 16"E).

By this experiment, the following was also found. One is the fact that if the number of azimuth mark observations is increased, the accuracy of the observation mean is improved and, as a result, apparent fluctuations are reduced as inferred in § 3. In the data of Fig. 8, the small variations of the mean (maximum range: 0.9 seconds, standard deviation: 0.3 seconds) are thought to demonstrate this fact.

Another fact concerns the azimuth mark observation time. The time required to double the number of readings was estimated to be 20 minutes plus 20 minutes, or a total of 40 minutes (20 minutes per person). However, when one person made twice as many readings using two targets, the time taken was 16 minutes on average. Because this is an experimental observation, one person performed both observation (reading) and recording. This result was obtained under such adverse conditions. If another person is provided as a recorder as in the usual absolute observation, the work will finish in 11 to 12 minutes or so. This is very short compared to the estimated 20 minutes. That is, even if the number of azimuth observations is doubled, the increase in required time is small if two targets are used in combination. As a matter of practice, this increase in time will not cause problems in the steady observation.

5. Closing remarks

We have always thought that the poor accuracy of the absolute declination observation is attributable to the poor accuracy of azimuth mark observation and that the number of azimuth mark observations must be increased to improve the accuracy. This greatly affects the instrumental error in commissioned certification treated as magnetic theodolite class 1 and the internal inspection. This also poses a grave problem, especially at branch observatories, when determining the instrumental error of a magnetic theodolite against the reference magnetic theodolite and when monitoring the instrumental error fluctuations.

This time, Owada, one of the authors, proposed increasing the number of azimuth mark readings at the observation for instrumental error certification. Thus, the relationship between the absolute declination observation and azimuth observation accuracy was compiled and reported as intended for a long period of time. For the steady geomagnetic absolute observation performed by the Observation Division and branches and the observation for instrumental error measurement including commissioned certification and internal inspection, it was decided to propose that increasing the number of azimuth mark readings is very effective as a means of improving the accuracy of absolute declination observation.

References

Hashimoto, M., Fukui, F., Takada, M., Ishida, N., Takizawa, N., Investigation of T-Mark (Azimuth Mark) reading daily variation, Gijutsu Hokoku, 102, 24-29, 1996 (in Japanese).

Memambetsu branch, New Azimuth Mark, 28th Geomagnetic Observation Technical Liaison Meeting, 2000 (in Japanese).